Idaho National Engineering and Environmental Laboratory

Next Generation Nuclear Energy Systems

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INEEL

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Generation IV Nuclear Energy Systems

Gas-Cooled Fast Reactor System	***GFR***
Lead-Cooled Fast Reactor System	***LFR***
Molten Salt Reactor System	***MSR***
Sodium-Cooled Fast Reactor System	***SFR***
Supercritical-Water-Cooled Reactor System	***SCWR***
Very-High-Temperature Reactor System	***VHTR***

- ***Each system has R&D challenges ahead – none are certain of success***

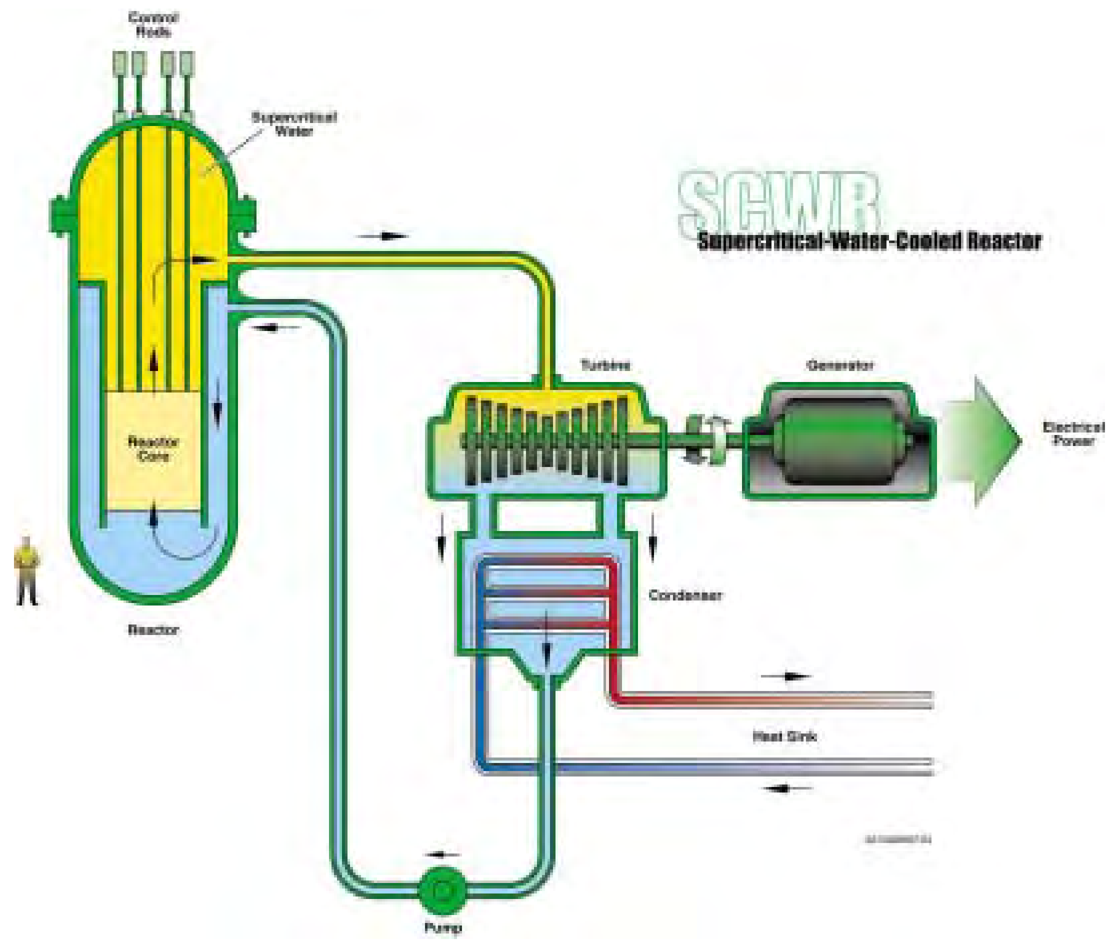
Supercritical-Water-Cooled Reactor (SCWR)

Characteristics

- ***Water coolant at supercritical conditions***
- ***550°C outlet temperature***
- ***1700 MWe***
- ***Simplified balance of plant***

Benefits

- ***Efficiency near 45% with excellent economics***
- ***Thermal or fast neutron spectrum***



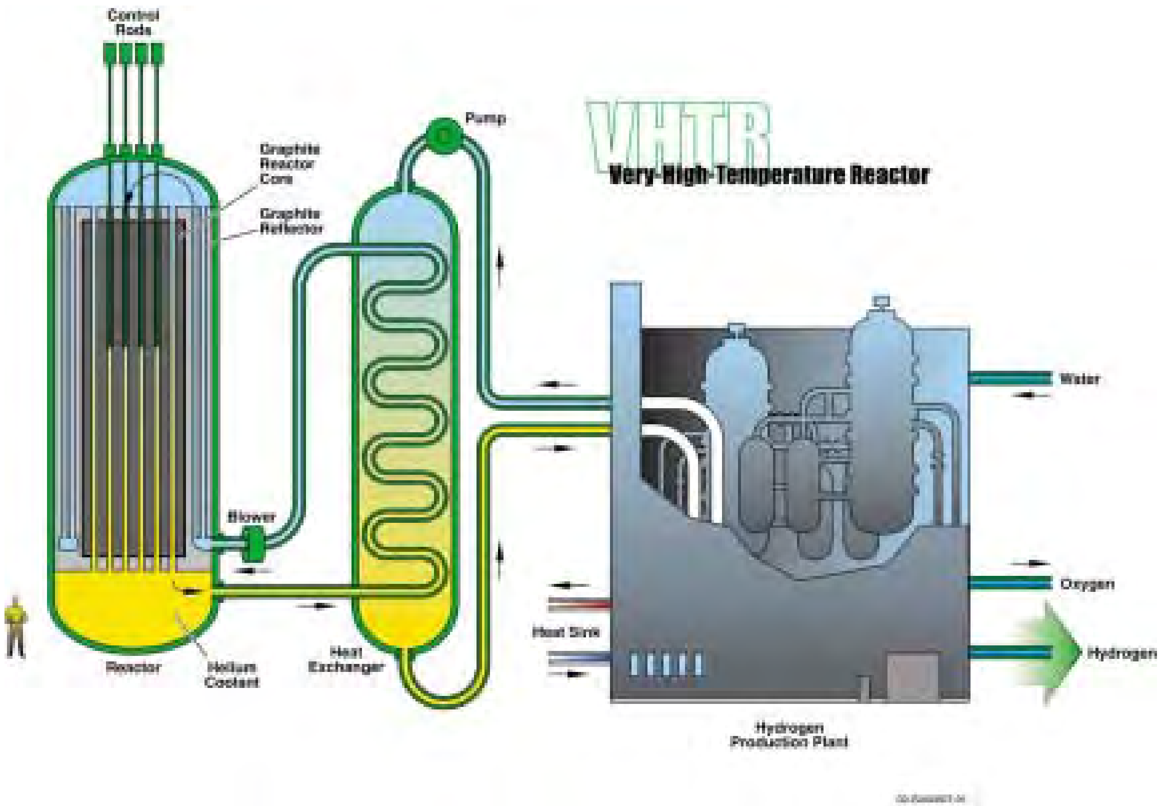
Very-High-Temperature Reactor (VHTR)

Characteristics

- **He coolant**
- **1000°C outlet temperature**
- **600 MWe**
- **Solid graphite block core based on GT-MHR**

Benefits

- **High thermal efficiency**
- **Hydrogen production**
- **Process heat applications**
- **High degree of passive safety**



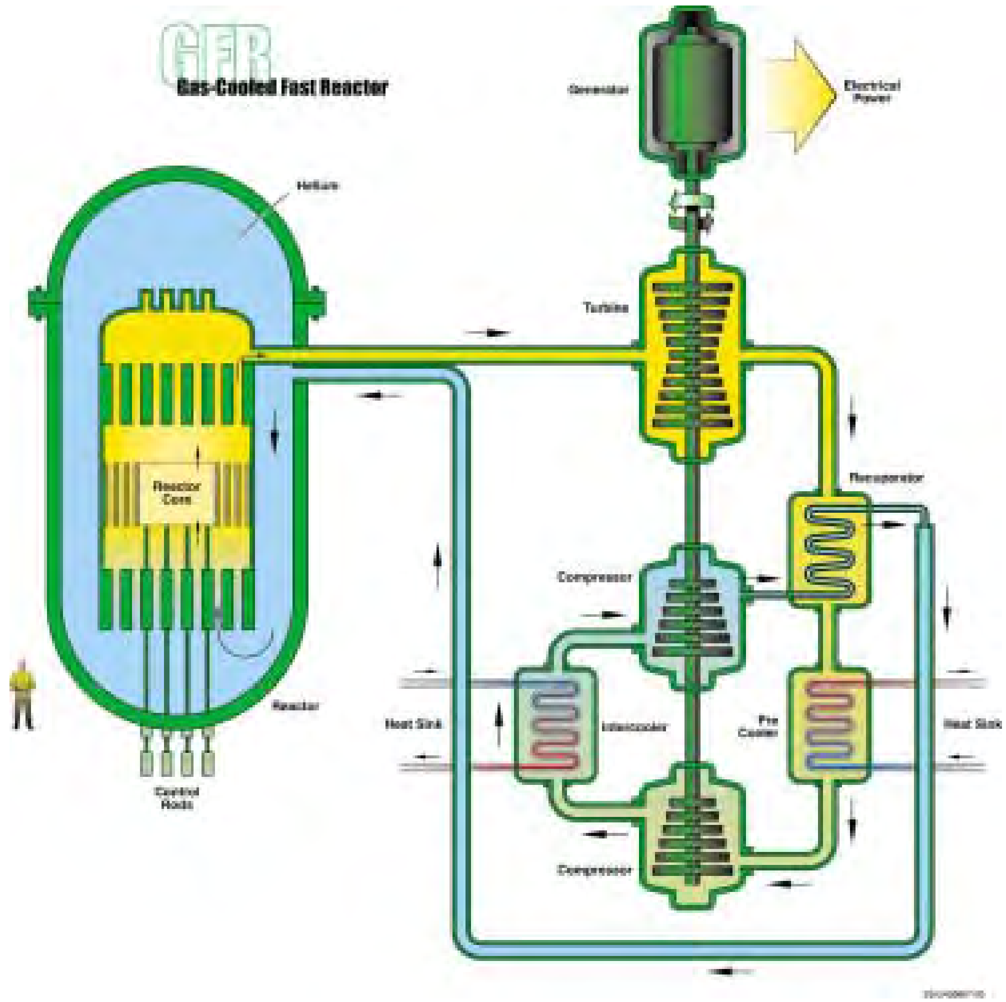
Gas-Cooled Fast Reactor (GFR)

Characteristics

- ***He coolant***
- ***850°C outlet temperature***
- ***Direct gas-turbine conversion cycle – 48% efficiency***
- ***600 MW_{th}/288 MW_e***
- ***Several fuel options and core configurations***

Benefits

- ***Waste minimization and efficient use of uranium resources***



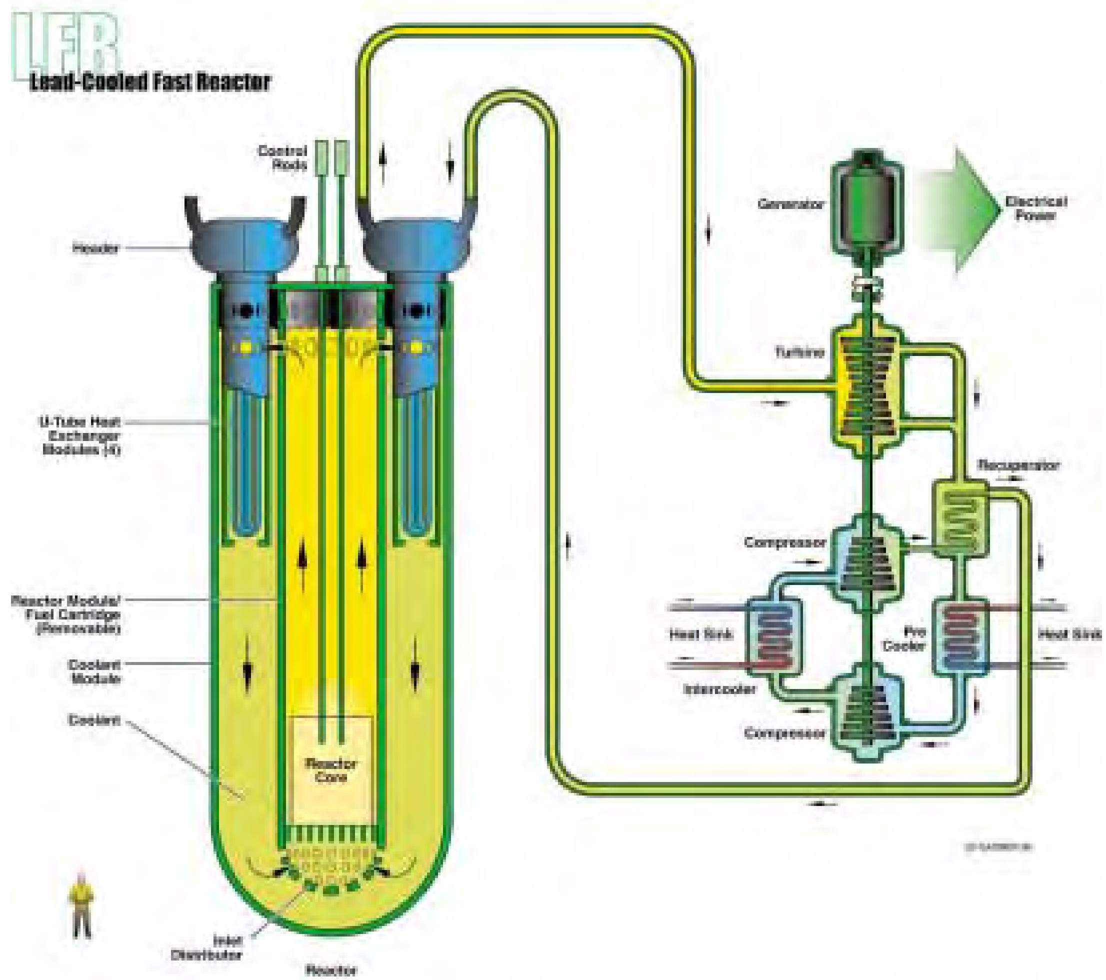
Lead-Cooled Fast Reactor (LFR)

Characteristics

- Pb or Pb/Bi coolant
- 550°C to 800°C outlet temperature
- 120-400 MWe
- 15-30 year core life

Benefits

- Distributed electricity generation
- Hydrogen and potable water
- Cartridge core for regional fuel processing
- High degree of passive safety
- Proliferation resistance through long-life cartridge core



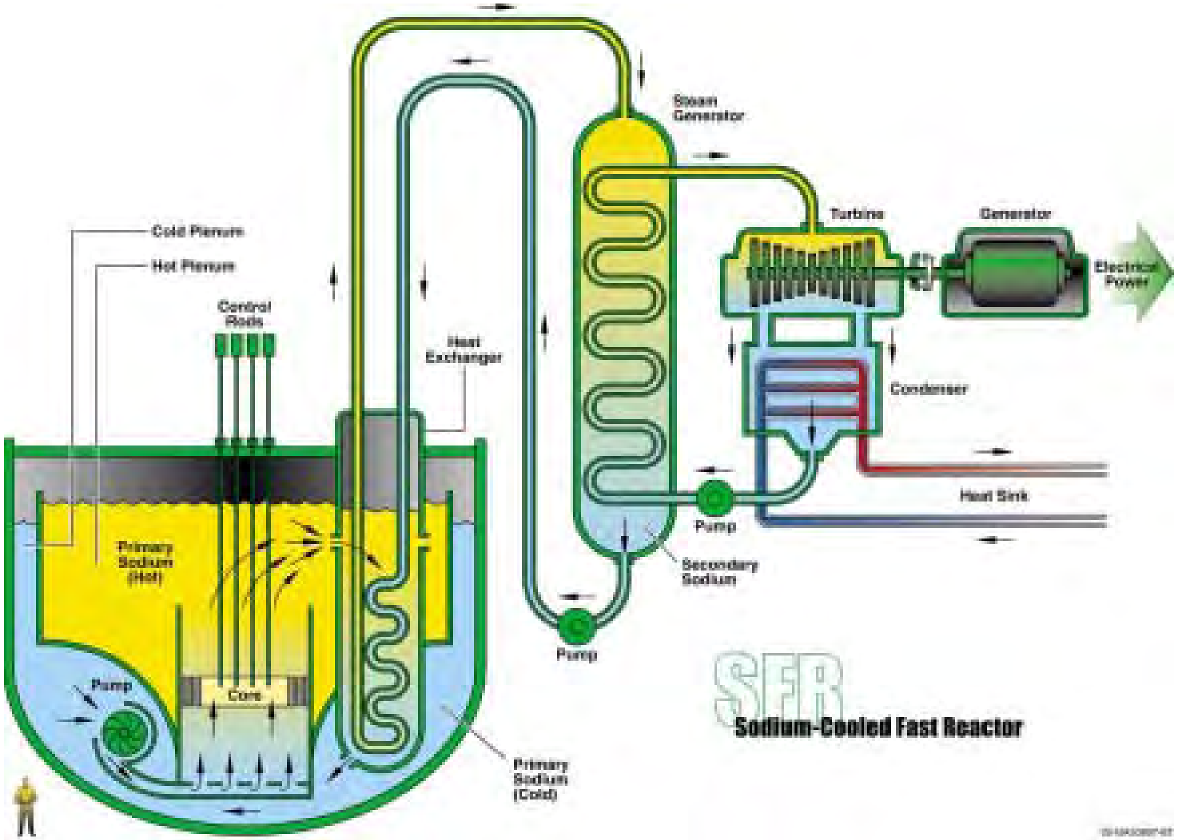
Sodium-Cooled Fast Reactor (SFR)

Characteristics

- ***Sodium coolant***
- ***550°C Outlet Temp***
- ***150 to 500 MWe***
- ***Metal fuel with pyro processing / MOX fuel with advanced aqueous***

Benefits

- ***Consumption of LWR actinides***
- ***Efficient fissile material generation***



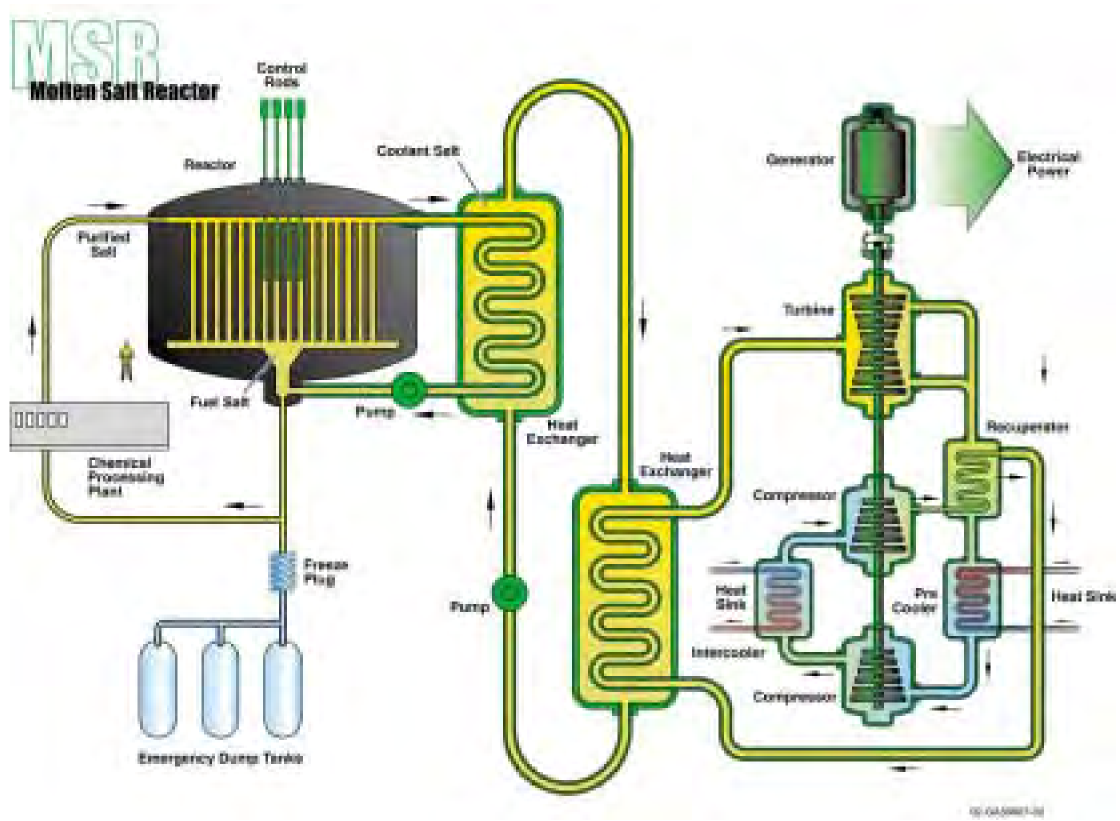
Molten Salt Reactor (MSR)

Characteristics

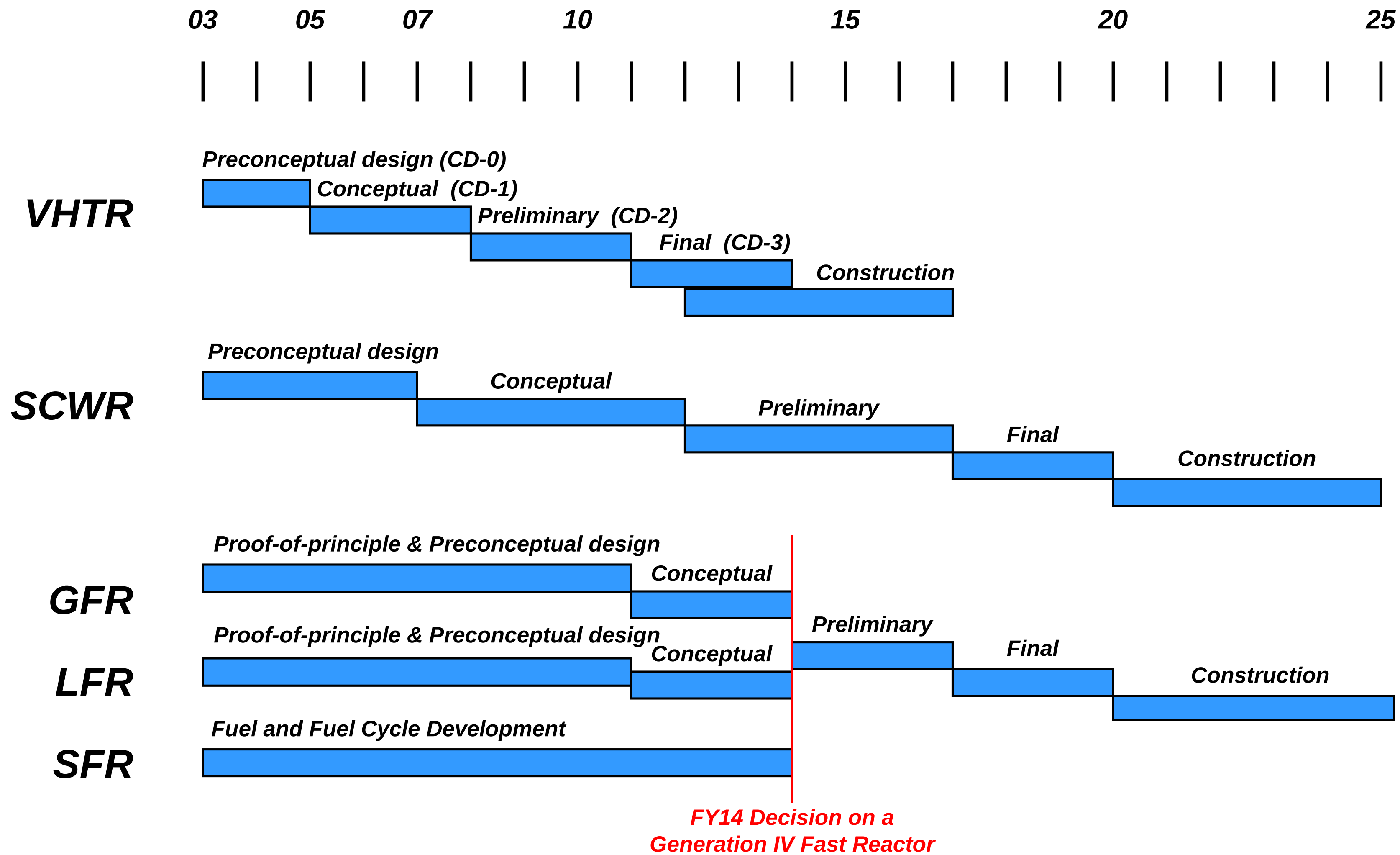
- Fuel: liquid Na, Zr, U and Pu fluorides
- 700-800°C outlet temperature
- 1000 MWe
- Low pressure (<0.5 MPa)

Benefits

- Waste minimization
- Avoids fuel development
- Proliferation resistance through low fissile material inventory



U.S. Generation IV Timelines (proposed)



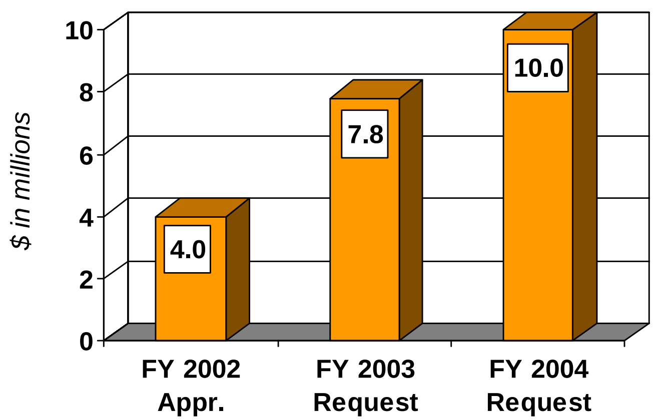
Generation IV Nuclear Energy Systems: Nuclear Power for a New Century

- *Developing advanced nuclear energy systems for deployment after 2010 and before 2030*
- *In September 2002, the 10-Nation Generation IV International Forum agreed on 6 advanced technologies, including:*
  - *- Very High Temperature Reactor (VHTR)*
  - *- Supercritical Water Cooled Reactor (SCWR)*
  - *- Gas Cooled Fast Reactor (GFR)*
  - *- Lead Cooled Fast Reactor (LFR)*

Planned Accomplishments -- FY 2004

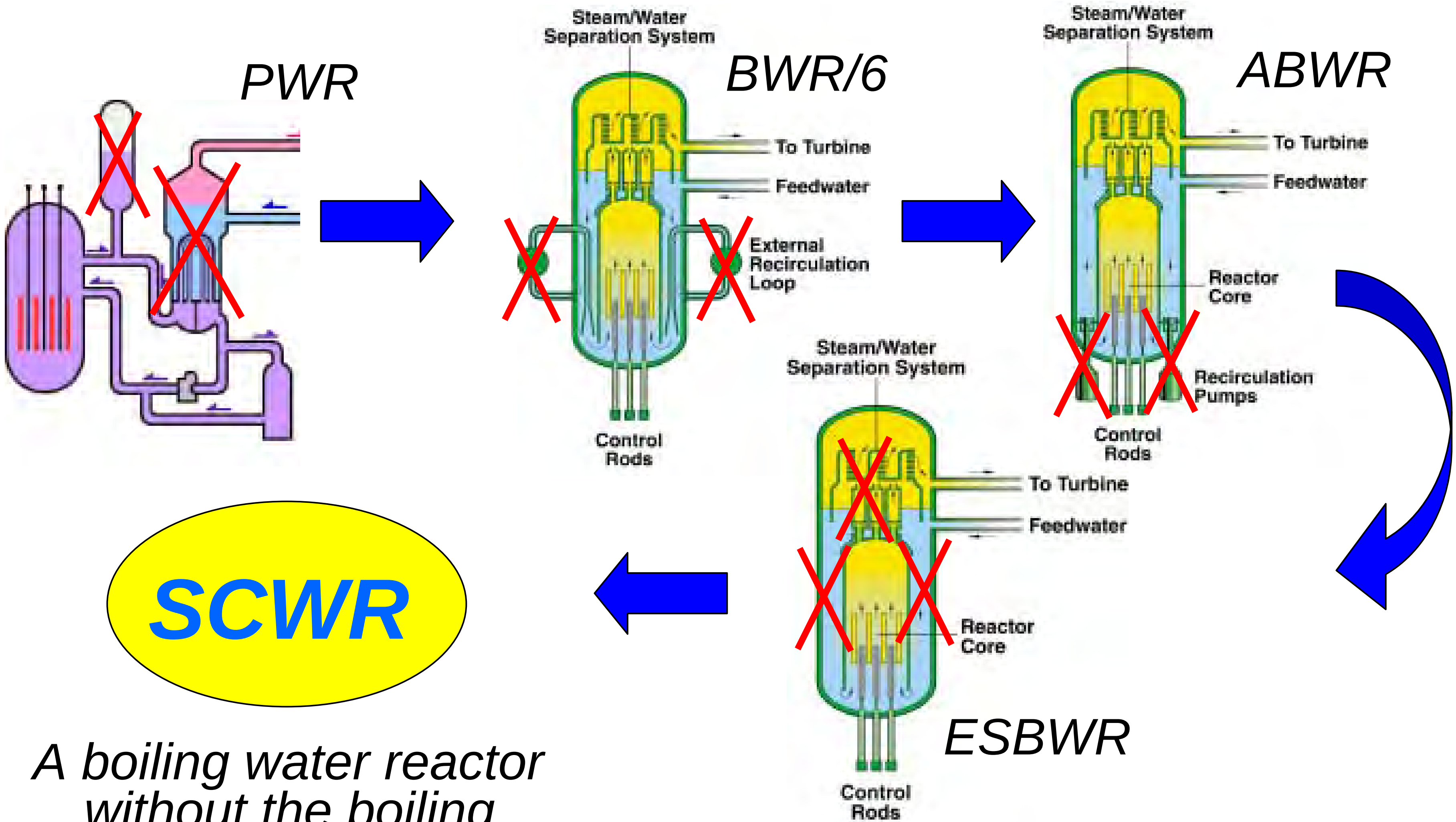
- *Conduct major VHTR trade studies*
- *Complete feasibility study on GFR fuels studies*
- *Initiate mechanical and irradiation tests on advanced materials*

Generation IV Nuclear Energy Systems Funding



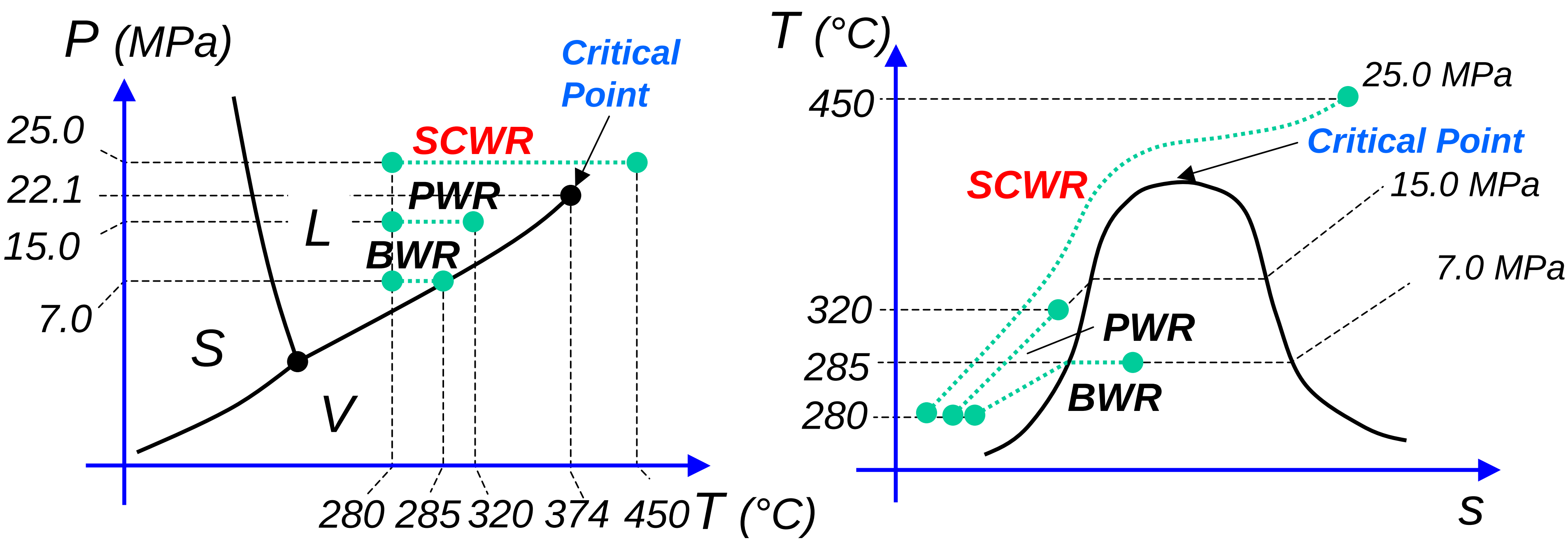
What is the SCWR ?

The next logical step in LWR path toward simplification



A boiling water reactor
…without the boiling.

Supercritical Water

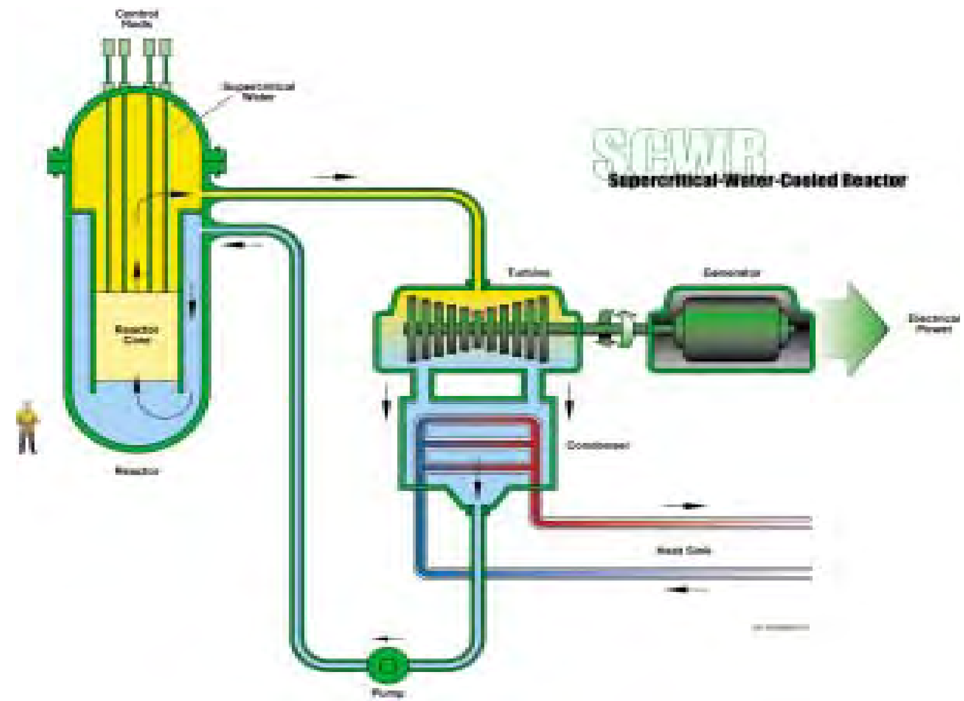


With operation above the critical pressure

NO CHANGE OF PHASE

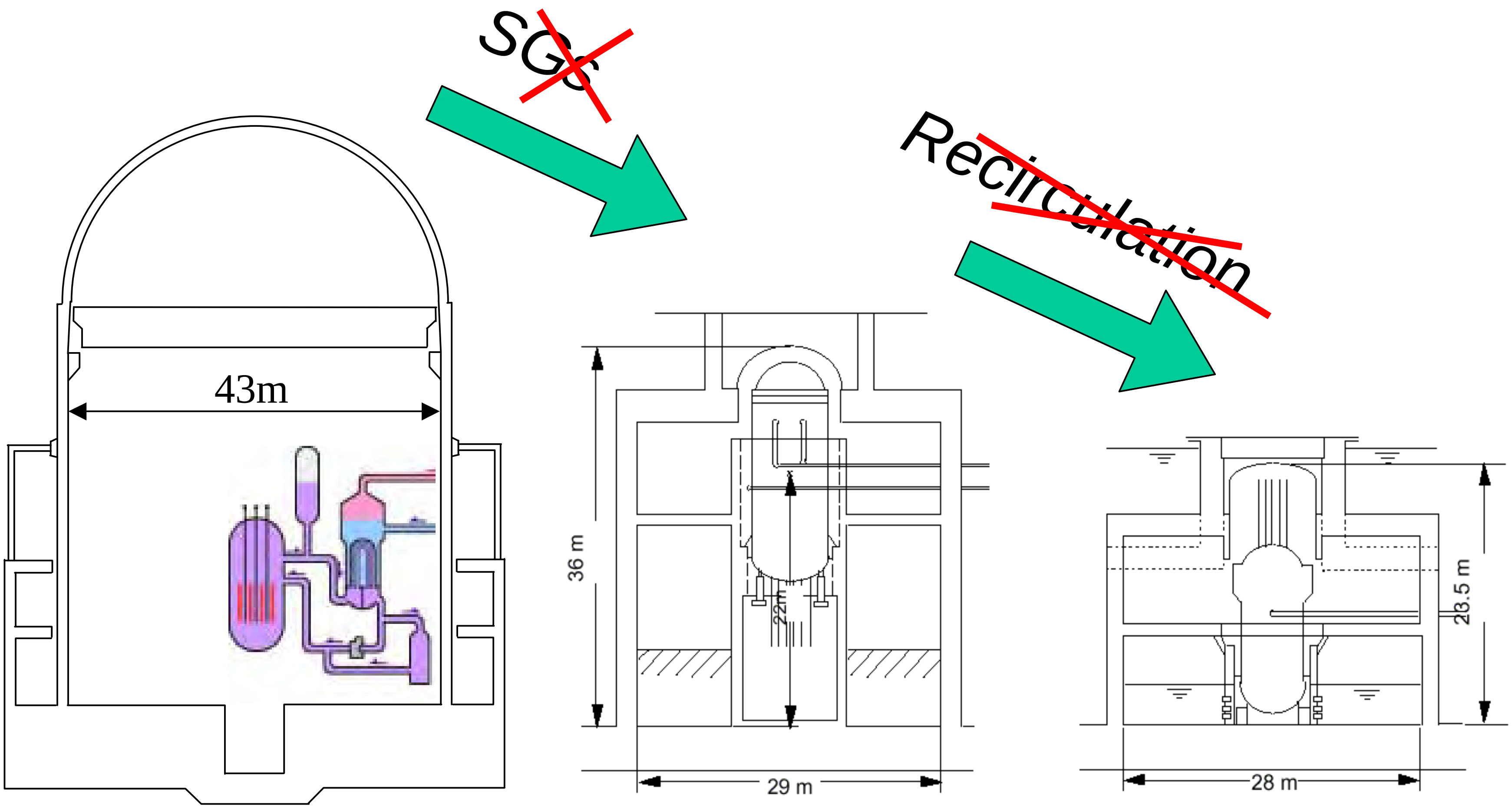
~~Phase Change~~

Simplified Once-Thru Direct Cycle



	Core	SGs / Steam Separators	Press.	Recirc. Pumps	Steam Lines	RPV	CRs	Containment
PWR	Yes	Yes	Yes	Yes	4	Small	Top	Large
BWR	Yes	Yes	No	Yes	4	Large	Bottom	Small
SCWR	Yes	No	No	No	2	Small	Top	Very Small

Very Small BWR-style Containment

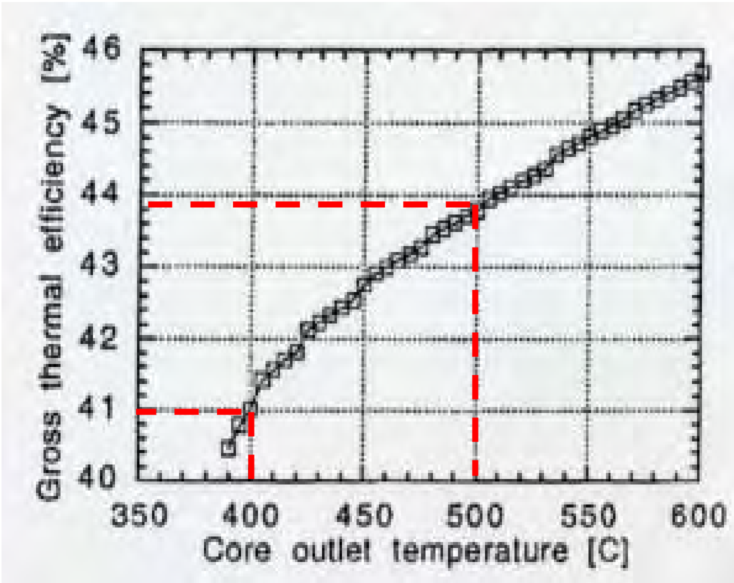


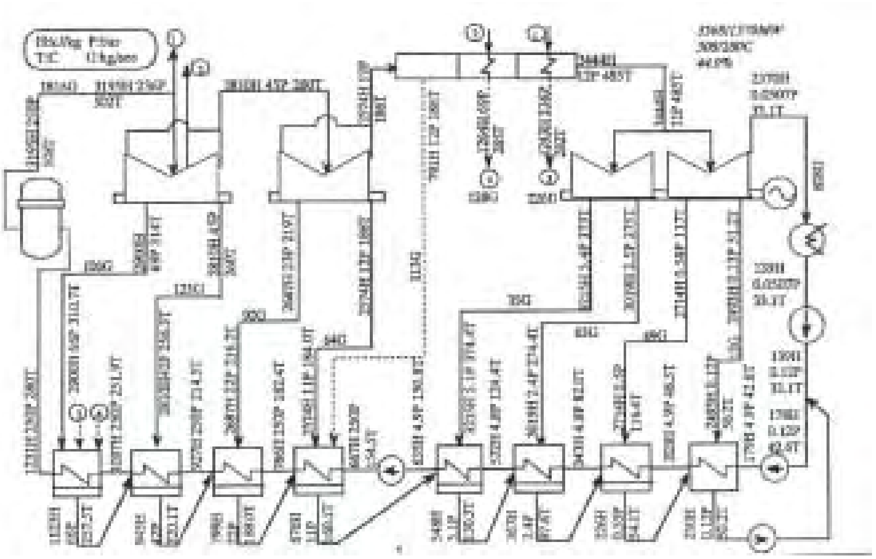
PWR(1100MWe)

ABWR (1350MWe)

SCLWR-H (1700MWe)

BOP and Thermal Efficiency





	Thermal Efficiency	Low Pressure Turbines	Turbine Speed	Condenser Modules
LWR	33-35%	3	1600 rpm	3
SCWR	41-44%	2	3600 rpm	2

For given thermal power, more electricity and smaller BOP

Benefits from Deployment of the SCWR

- *Reduced capital cost from plant simplification and high thermal efficiency. The Gen-IV estimates are $900/kWe and ¢2.9/kWh.*
- *Could combine two proven technologies: LWRs and supercritical-water fossil plants.*

Open Issues

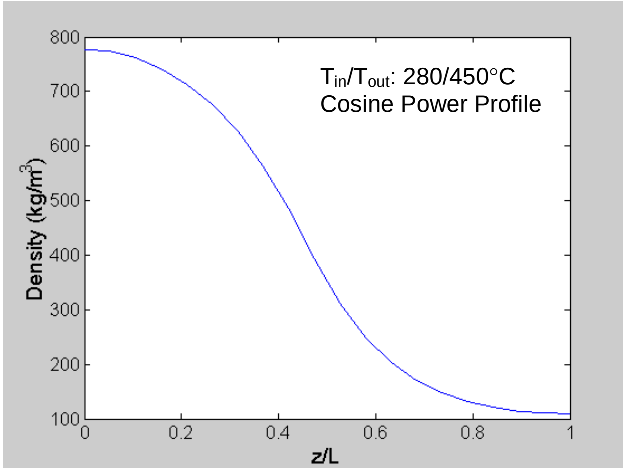
- *Safety*
- *Stability and Control*
- *Core Design*
- *Core Materials*

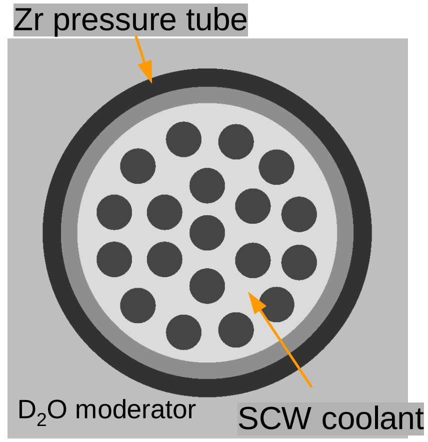
Core Design

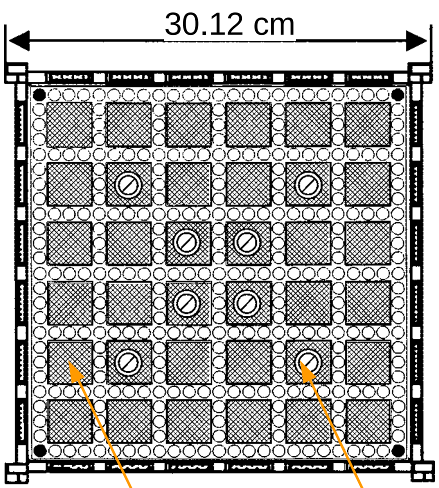
Low average density in the core

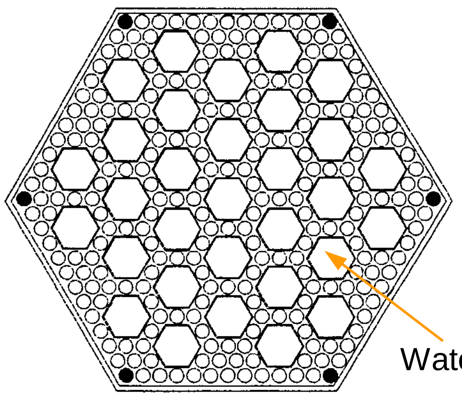
Fast core is possible

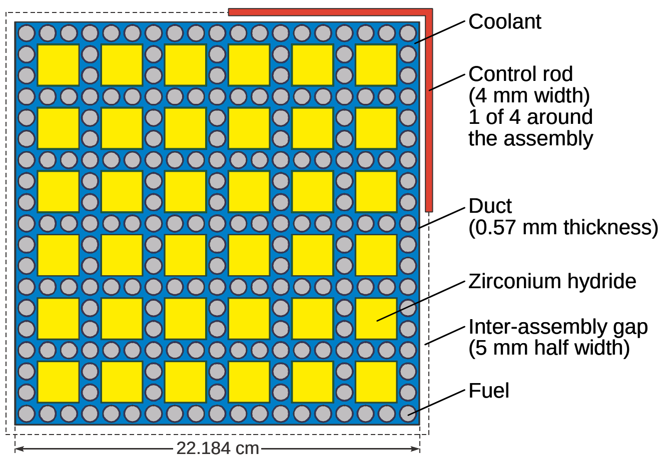
Thermal core needs dedicated moderator





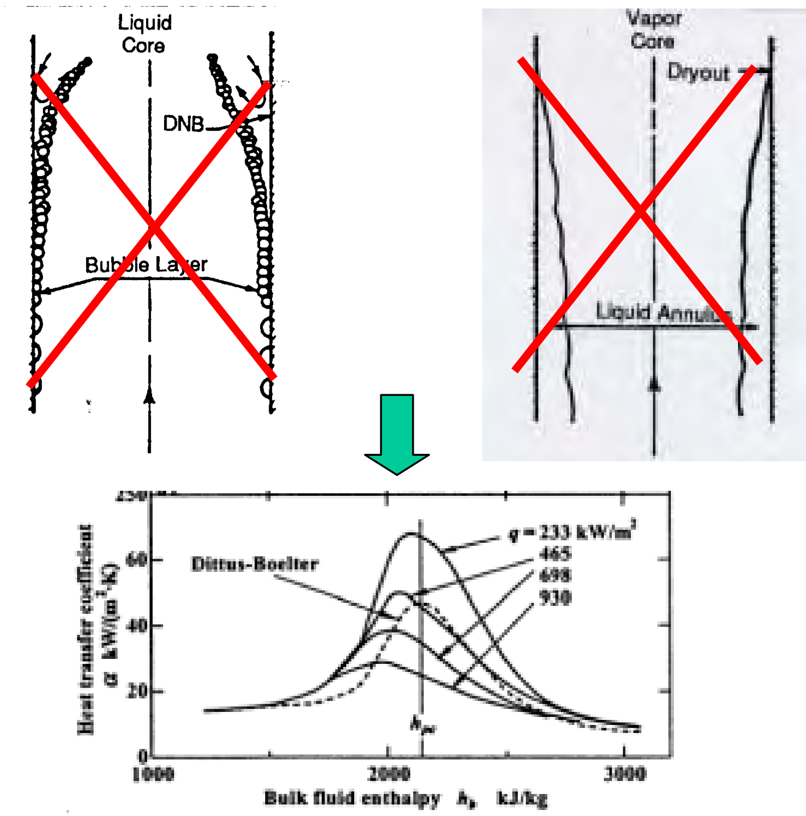






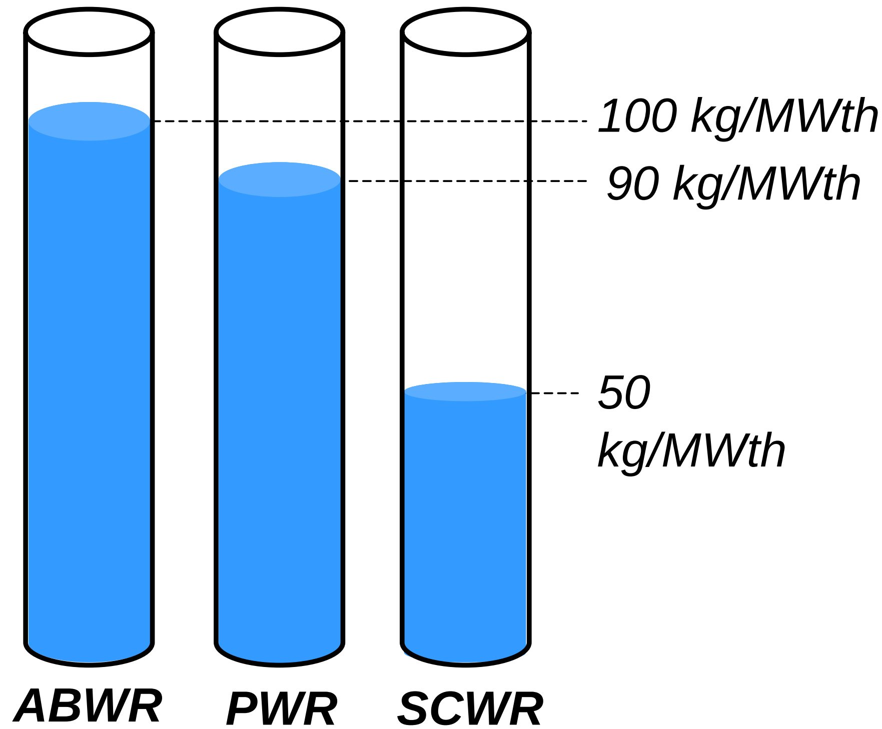
Safety

One Advantage



Elimination of the boiling crisis under normal operating conditions

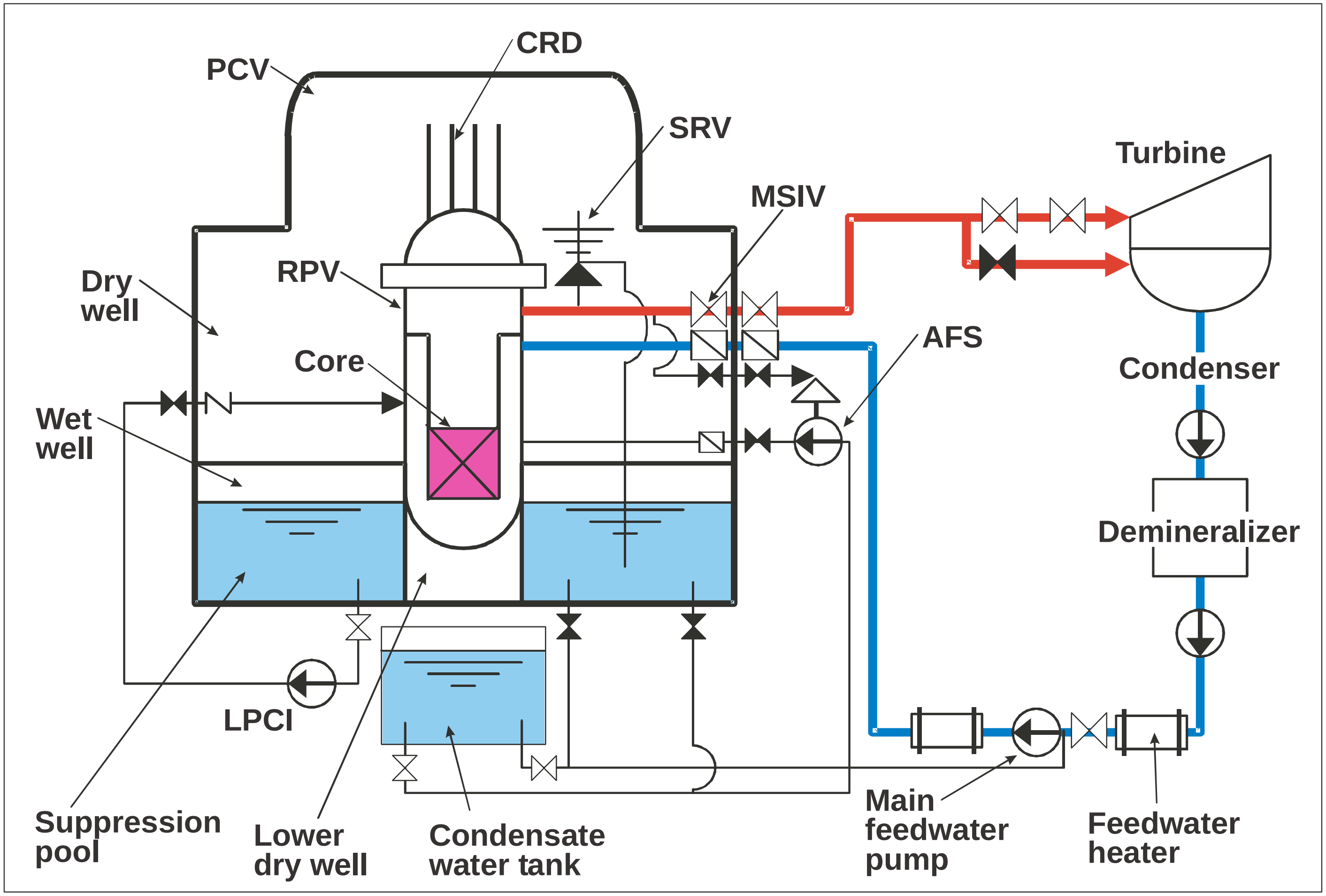
One Disadvantage



Low primary water inventory

Safety

SCWR safety is deemed comparable with ABWR.



Can it be designed with ESBWR-type passive safety systems?

Core Materials—Open Questions

- Effect of radiation on corrosion and SCC
- Effect of radiolysis on coolant chemistry
- Effect of radiation on microstability
- Effect of radiation on mechanical properties

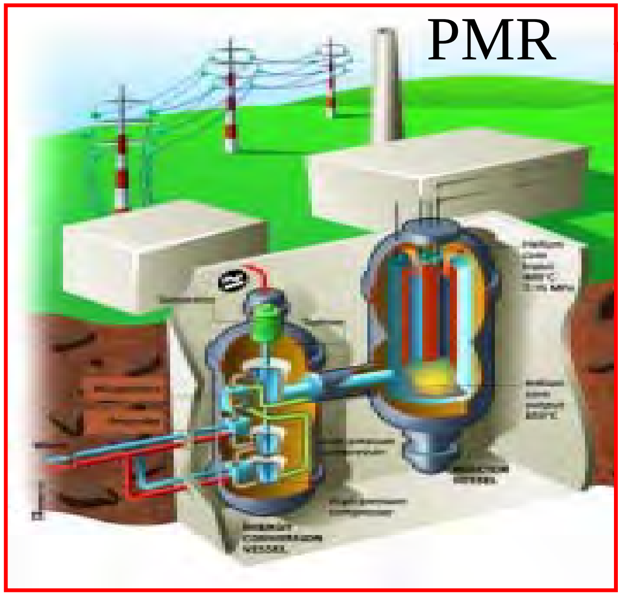
SCWR Summary

- *Key features of SCWRs are high thermal efficiency and plant simplification for improved economics*
- *Major R&D gaps include in-core materials development and demonstration of adequate safety and stability, which will be addressed in the Gen IV program*
- *Broad international interest in the concept: 10 countries involved with national laboratories, universities and industry*

Sequenced Development of High-Temperature Gas-Cooled Nuclear Energy Systems

R & D
- Fuel particles
- Materials
- He systems technology (850°C)
- Computer codes
- Fuel cycle

PMR



VHTR

> 950°C for VHT heat process

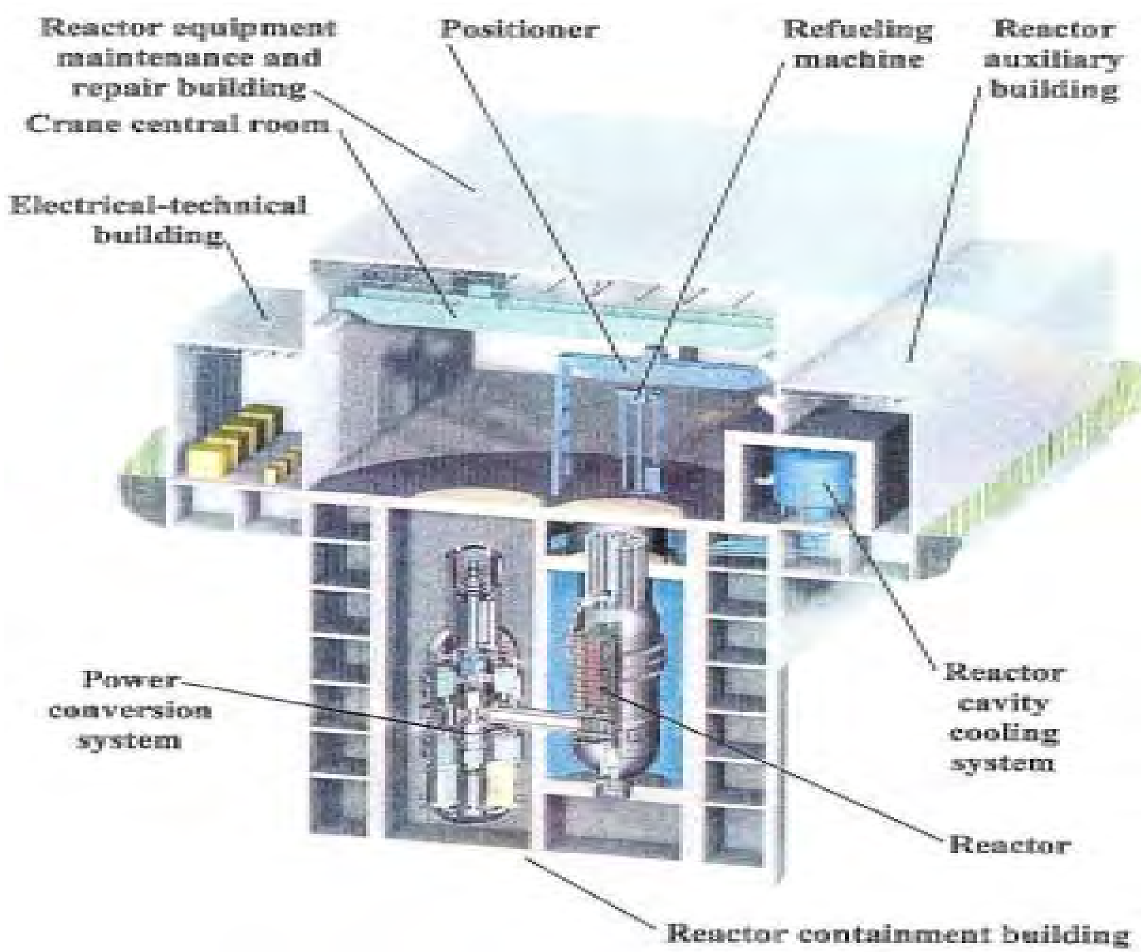
R & D
- VHT materials
- IHX for heat process
- ZrC coated fuel
- I-S cycle H2 production

GFR

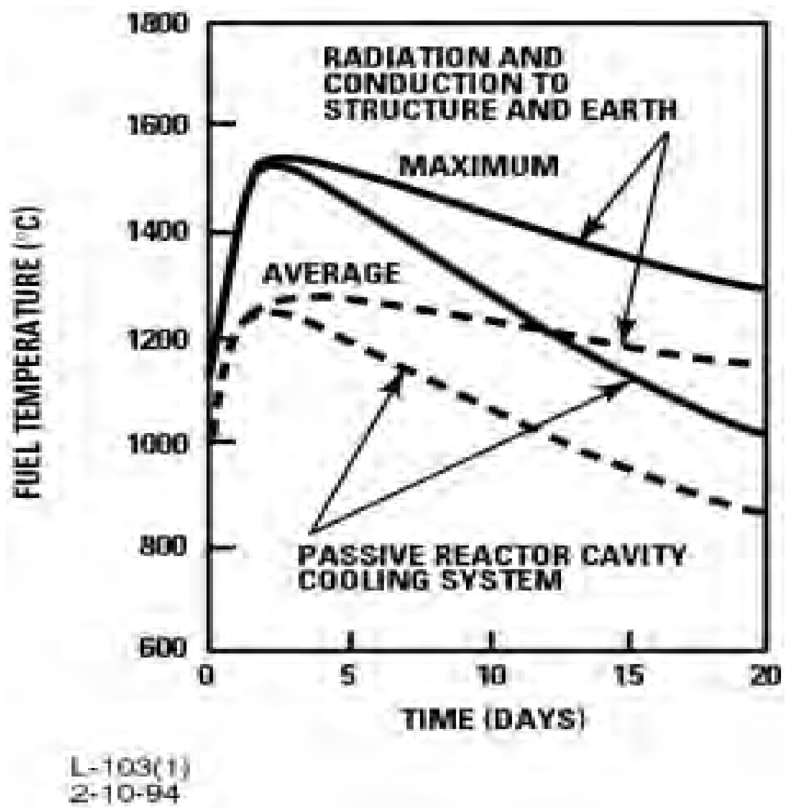
Fast neutrons
Integral fuel cycle for high sustainability

R & D
- Fast neutron fuel
- Fuel cycle processes
- Safety systems

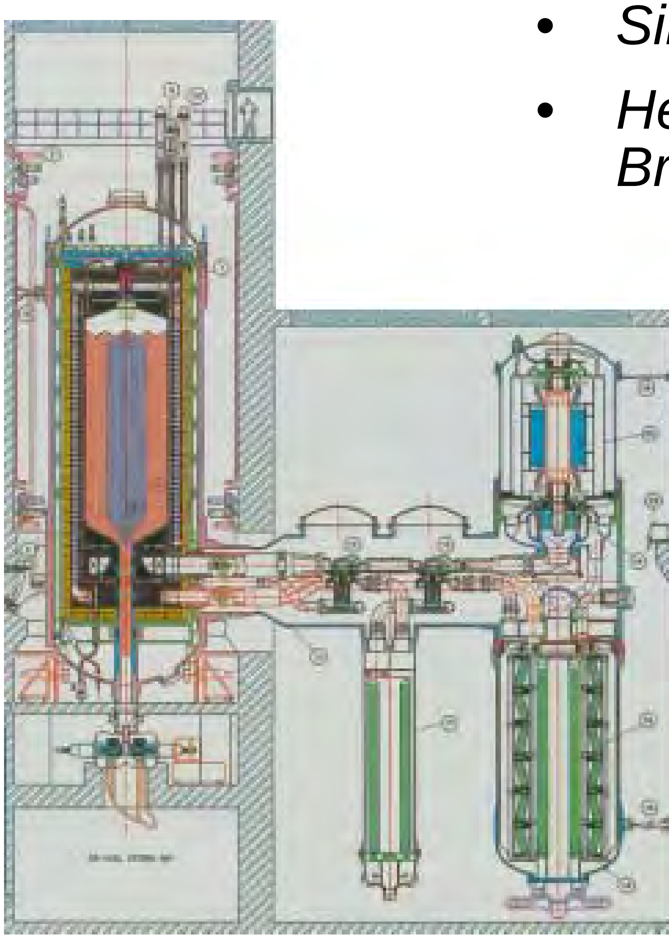
Conceptual Prismatic Modular Reactor (PMR)



PMR Response to Loss of Coolant



High-Temperature, Gas-Cooled, Pebble-Bed Modular Reactor



- *Simplified design; modular construction*
- *Helium gas coolant; direct-cycle gas turbine Brayton system (50% thermal efficiency)*
- *Graphite reactor core; high-temperature, coated-particle fuel*
- *"Meltdown proof" passive safety*
- *New economic opportunities*
  - *100 MWe to match power-growth demand*
  - *Factory fabrication vs. on-site custom construction*
  - *Dual-mission-capable (electricity and H_2)*

Very High Temperature Reactor Systems (VHTR)

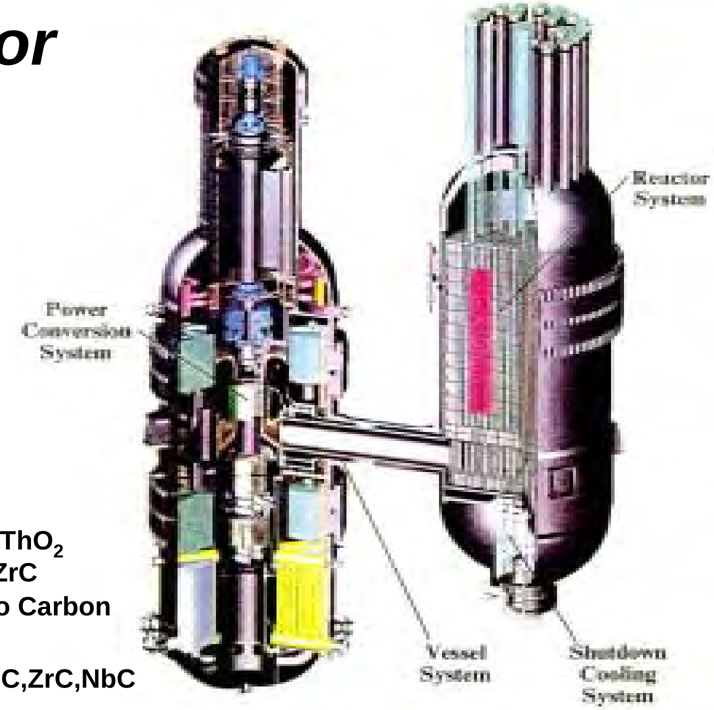
- ***A near term Generation IV system***
  - ***estimated 2017 deployability***
  - ***builds upon PBMR and GT-MHR NP 2010 designs***
  - ***could be pebble bed or prismatic core***
- ***Shows promise for***
  - ***Gains in sustainability and flexibility***
  - ***Significant advance towards safety goals***
  - ***Comparable economics***
  - ***Bridge to hydrogen economy***

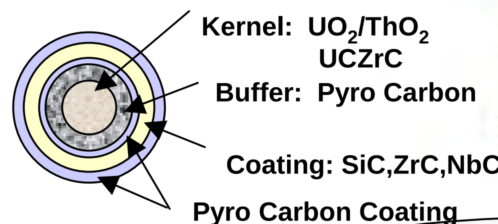
Main VHTR Features

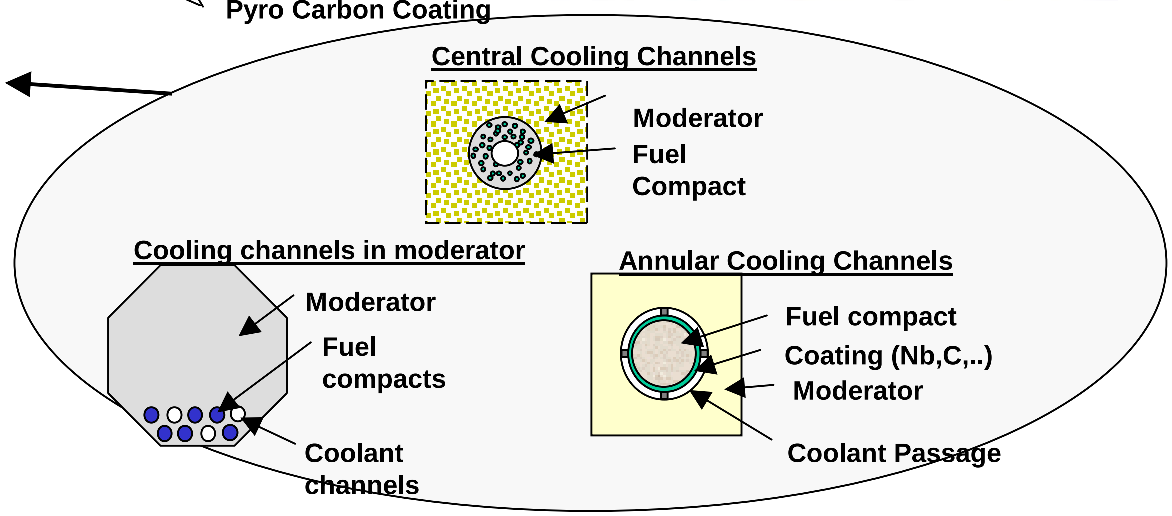
- Extension of prismatic modular reactor (PMR) and of pebble bed modular reactors (PBR)
- Higher coolant core outlet temperatures to enhance process heat applications
- Direct Brayton cycle energy conversion
  - He coolant, >900ºC outlet temperature
  - Efficient electricity generation (>50%) and/or H_2 production (e.g. hot electrolysis)
- Thermochemical water splitting
- Deployment in crude oil refining and petrochemistry by substituting process heat

Very High Temperature Reactor

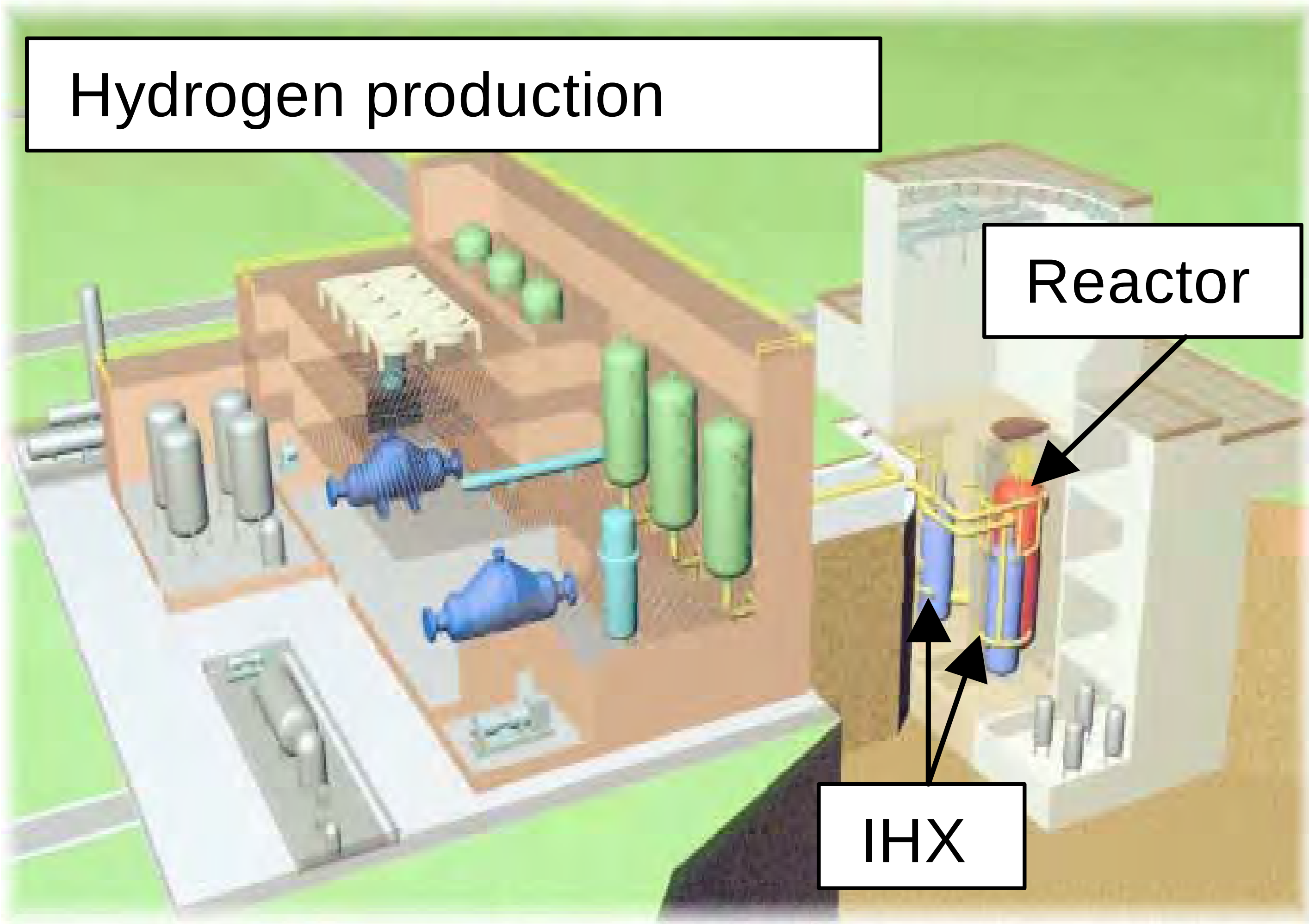
- ***High temperature source for range of process heat applications***
- ***High Temperature Considerations***
  - *Advanced particle coatings for FP retention at elevated temperatures*
  - *Advanced fuel materials (carbides, nitrides, cermets,etc)*
  - *Fuel element design for reduced temperature drop - fuel to coolant*
  - *Control materials and design*
  - *Structural materials*
  - *Heat exchanger / recuperator materials and design*







VHTR Plant Schematic

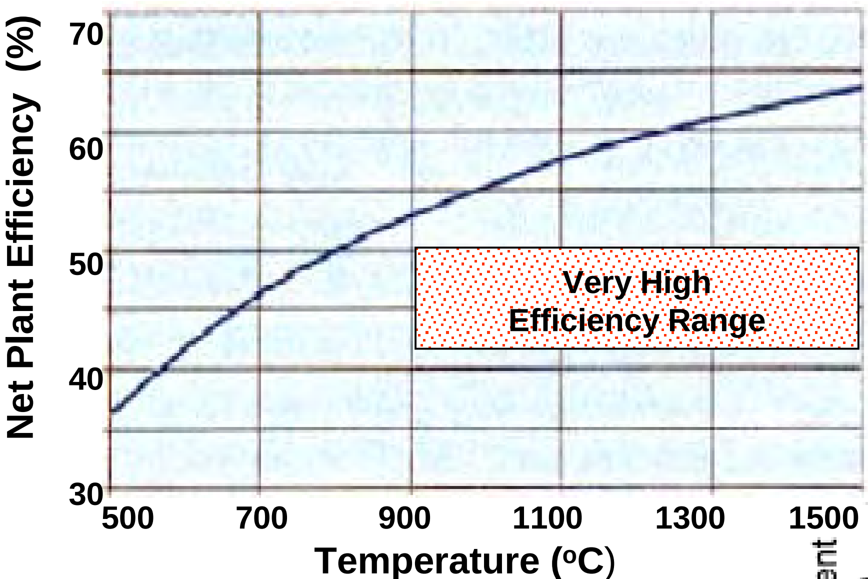


Energy Conversion Approaches

- High temperature Helium Brayton Cycle
- Hydrogen Production--
  - Steam reforming of methane
  - Thermochemical water splitting
  - Thermally assisted electrolysis

High Outlet Temperatures Provide Increased Electrical Conversion Efficiency

High efficiency benefits all aspects of system performance

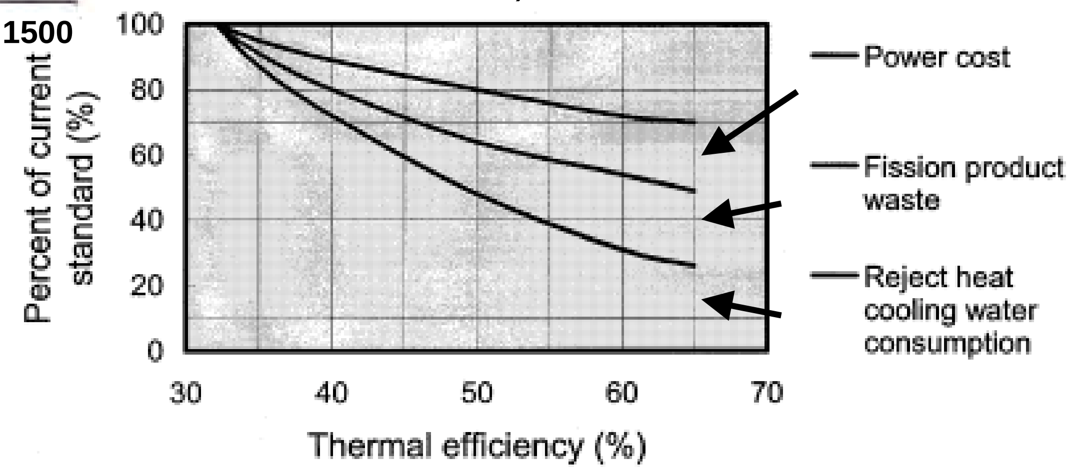


Efficiency vs Turbine Inlet Temperature for Recuperated Brayton Cycle)

GE Power Systems MS7001FB

•Single crystal Technology (GE's jet engines)

•2500° F-class firing temperature (1644 K, 1371 °C)

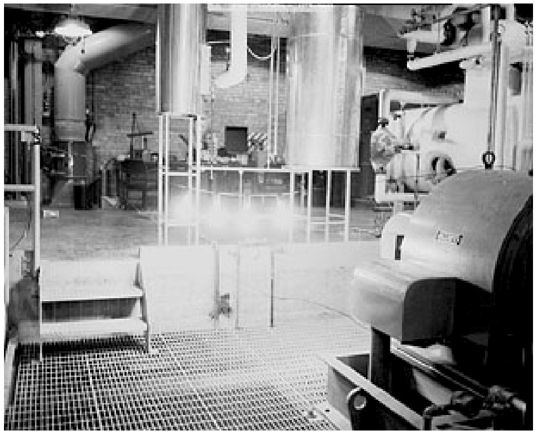


Very High Temperature Reactor Issues

- Cost / Benefit -- increased performance at higher temperatures versus potential impacts on cost/reliability
- Proximity of high temperature process heat application to nuclear system – safety, heat transport
- Materials lifetime at elevated temperatures

Fast Reactors

- Fast reactor technology and experience has been with liquid metal coolants (primarily sodium) where
  - High burnups can be achieved (~200 MWd/kg)
  - The destruction of plutonium and minor actinides is optimized due to the high fission to capture ratio
  - The fuel can be designed for multiple recycle



EBR-I

EBR-II

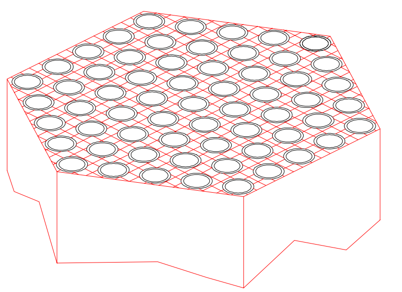
Rationale for Gas Fast Reactors

- *A successful combination of the two technologies would be valuable in meeting Generation IV objectives*
- *GFRs share the sustainability attributes of fast reactors*
  - *Effective fissioning of Pu and minor actinides*
  - *Ability to operate on wide range of fuel compositions ("dirty fuel")*
- *Gas coolants offer advantages of*
  - *Chemical inertness (if using He)*
  - *Small coolant void reactivity ($<\beta_{eff}$)*
  - *Eased in-service inspection*
  - *Potential for high temperature and direct cycle conversion (if using He)*
  - *Potential for high thermal efficiencies at lower temperatures (if using supercritical CO_2)*
- *High temperature enables new applications, including thermochemical hydrogen production*

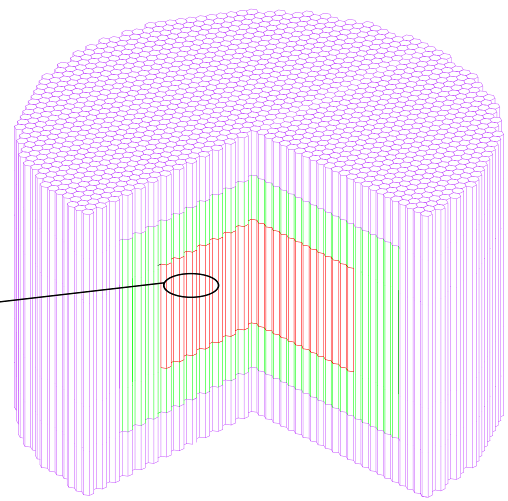
Main GFR Features

- Closed fuel cycle system with full TRU recycle
  - Co-located fuel cycle facility
- Hardened/fast spectrum core
  - Reduced moderation relative to thermal GCRs
- Direct Brayton cycle energy conversion
  - He coolant, 850ºC outlet temperature (reference)
  - Supercritical CO_2 coolant, 550-650ºC outlet temperature (option)
  - Efficient electricity generation, potential for H_2 production
- Possible indirect cycle
  - He on primary, supercritical CO_2 on secondary
- Estimated deployment time: 2025

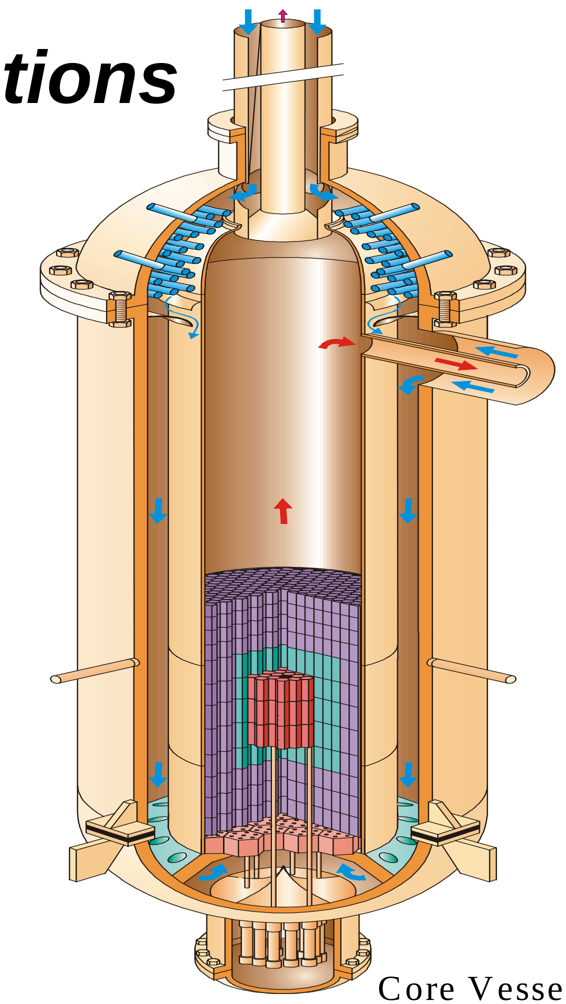
Gas-cooled Fast Reactor (GFR)
Example of candidate design options



Composite Ceramics
Fuel Element

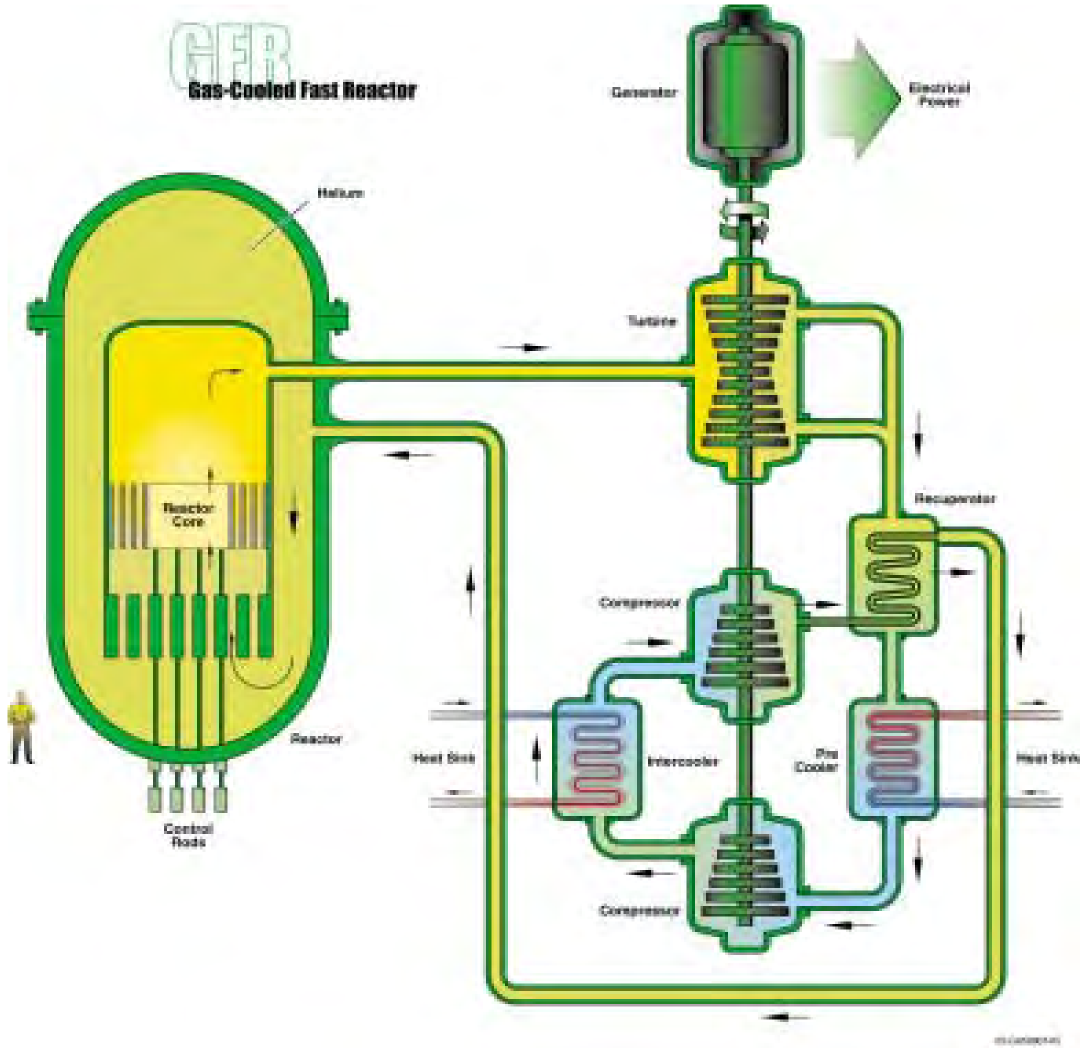


Core Lay-out



Core Vessel

GFR Plant Schematic (direct cycle)



GFR Technical Issues

- ***Achievable degree of passive safety***
- ***Capability of materials (including fuels) to withstand targeted temperature and fast fluence conditions***
- ***Effectiveness of recycle technologies***
  - ***Actinide recovery factors***
  - ***Waste quantity and durability***
- ***Feasibility of economic design***

Pb, Pb-Bi Cartridge Core Concept

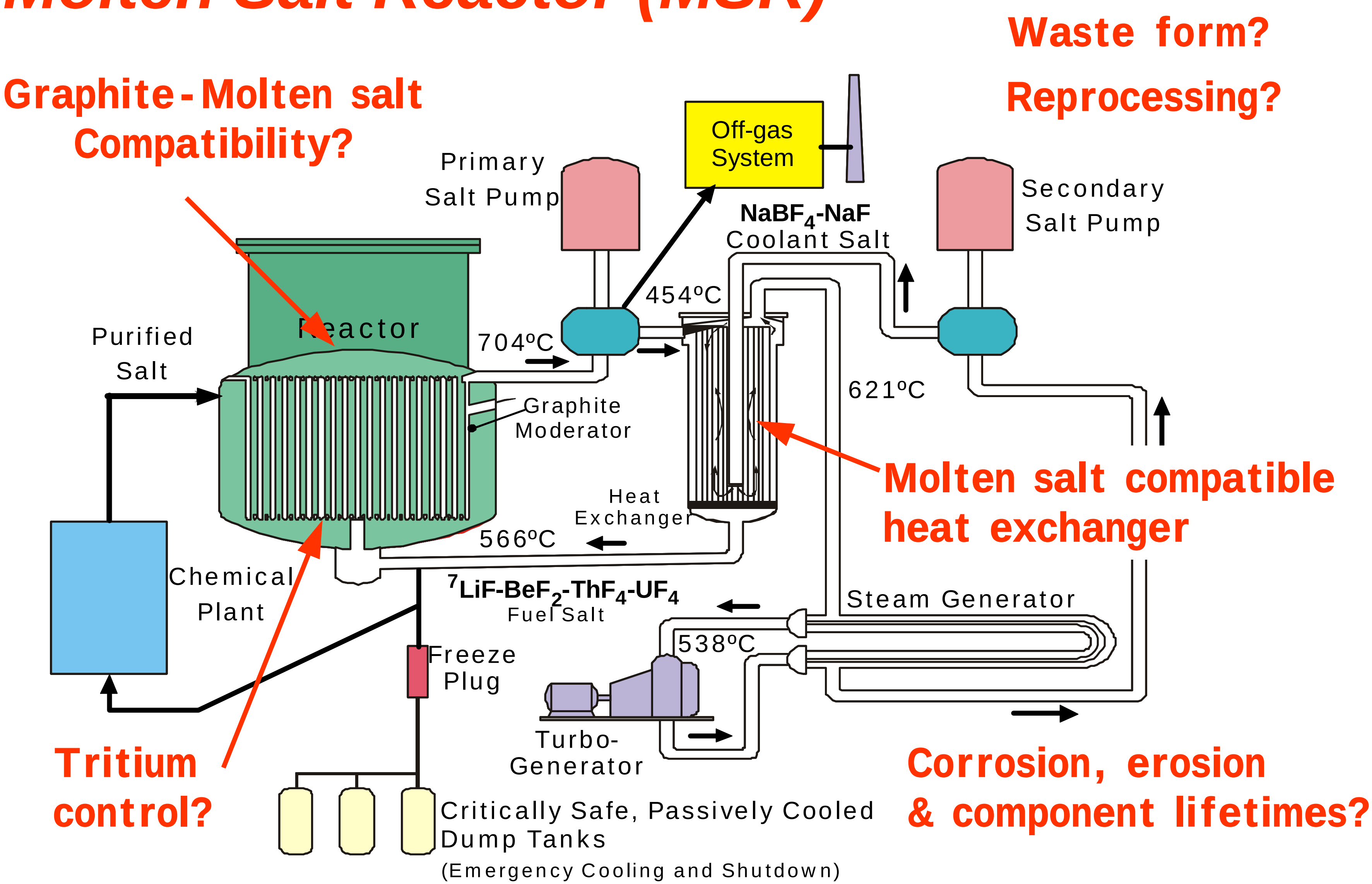
Description

- ***Small (125 to 400 MW_t)***
- ***Transportable (Factory Built Turnkey Plant; Rapid Installation & revenue generation)***
- ***Long Refueling Interval: 15-20y; (internal conversion ratio 1.0)***
- ***Cassette or Entire Module refueling***
- ***Derated Power Density (LWR range) (Natural Circulation Cooled)***
- ***Passive Load Follow/Passive Safety (No safety Functions for BOP)***

Options

- ***High Temperature: Alternative Energy Products (Process Heat Hydrogen, O_2, Desalinated water)***

Molten Salt Reactor (MSR)



MSR—Key Features

- Alkali metal fluoride solute–Thorium-Uranium Fluoride Fuel
- Circulating molten fuel
- Fuel and Coolant one and the same
- Thermal breeder, actinide burner, or once-through cycle
- Large negative reactivity coefficient, passive cooling safety features
- Fission products and actinides soluble in molten salt
- Online feeding, processing and fission product removal
- Passive cooling, failsafe drainage
- High temperatures—high efficiency and potential for thermochemical hydrogen production